**Reference [9]: Proceedings of IEEE AeroSense 2001, Paper No. 470, March, 2001, Big Sky Montana, in press.**

# Effects of Proton Irradiation on InGaAs/AlGaAs Multiple Quantum Well Modulators[1]

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*Abstract* Recently large area multiple quantum well (MQW) optical modulators have been coupled to corner-cube optical retro-reflectors to allow free-space optical communications using a lightweight, low-power device. A pointing/tracking system and laser are required only on one end of the link. Such a system is attractive for ground-to-space links or space-to-space communication between a satellite and a microsat. An important question for these potential space-borne systems is the radiation tolerance of the MQW modulator, which is the principle active component. To investigate this subject, we irradiated three 0.5˚cm diameter InGaAs/AlGaAs modulators using a sequence of bombardments of 1˚MeV protons. One of the devices was irradiated while under a normal operating reverse bias voltage of 15˚V; the other devices were unbiased. After each exposure the electronic, optical and modulation characteristics of the modulators were evaluated. No degradation was observed until a cumulative fluence of 1˚x˚10$^{14}$ protons/cm$^{2}$, equivalent to an ionizing radiation dose of approximately 200˚Mrad(Si).

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## 1. INTRODUCTION

Free space optical communication has emerged in recent years as an attractive alternative to conventional radio frequency (RF) systems. This is due to the increasing maturity of lasers and compact optical systems as well as the inherent advantages of this approach, including very large bandwidth, low probability of intercept, and immunity from interference. These features are inherent in the short wavelength of optics, but such systems require high quality telescopes and extremely accurate pointing and tracking. As a result, optical communication systems can have a large system impact in terms of weight, power and platform stability. Such systems are also inherently complex. These costs are acceptable in many systems, but if the platform is small or has little available power, the requirements of a conventional optical link may be prohibitive.

The low divergence of optics is used in conventional optical communication systems to allow very high bit-rate (~Gbits/sec) links at long range. However, optics low divergence can be used in another way: to enable a new kind of communication system that would be impractical at longer (RF) wavelengths. Rather than using two laser transmitters with their associated gimbaled telescopes and pointing/tracking systems, it is possible to establish a two-way optical link using a single conventional laser transmitter and tracker. This transmitter is located on a large platform (or at a ground station) that has sufficient power, payload capacity, and platform stability to operate it. It can transmit data to a second small platform conventionally, by modulating its laser with the desired signal. If the laser is strong enough the small platform can receive the data with a detector with a wide field of view, obviating the need for a large pointed receive telescope. However, such a conventional system does not allow the small platform to transmit data back to the large platform. To enable the small platform without a laser to return data to the large platform, the Naval Research Laboratory (NRL) has investigated using a modulating retro-reflector (MRR).

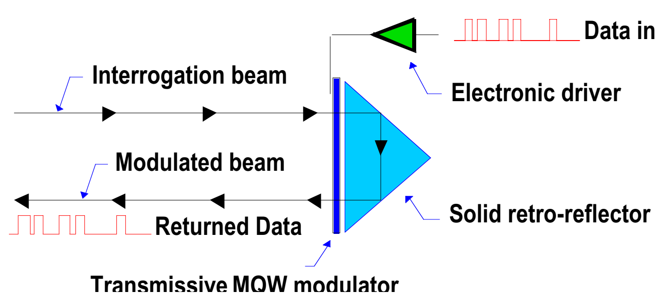


Figure 1 — Principle of operation for a modulating retroreflector showing the impression of an electrical pulse onto the incident CW laser beam.

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An optical retro-reflector is a passive optical system that reflects light incident upon it exactly back along its path of incidence, as shown in Figure 1. A typical retro-reflector consists of three mirrors mounted in the configuration of the corner of a cube. However, most systems use solid glass retroreflectors with anti-reflection coatings on the incident face and protected silver on the back faces. Retro-reflectors typically have a large field of view (about 20 degrees full angle) and very high efficiency. Retro-reflectors can be mounted in a hemispherical array to expand the field of view as has been implemented to allow millimeter accuracy laser ranging of satellites.

Retro-reflectors can also act as one element of an optical communication system. By mounting an electro-optic shutter in front of the corner-cube, the retro-reflected beam can be modulated. On a small platform, such a modulating retro-reflector can transmit data optically, without requiring a laser or pointer-tracker on the platform itself. In operation, the large platform would illuminate the small platform with a continuous-wave (unmodulated) laser beam. This beam would strike the modulating-retro and be passively reflected back to the large platform. The shutter would then be modulated with an electrical signal that carries the small platform s data. This impresses the data stream upon the retro-reflected beam, which then carries it back to the large platform, as shown schematically in Figure 2.

Such a system can be lightweight and low power. In addition, if an array is used, the small platform need only be pointed toward the large platform with an accuracy equal to the field of view of the array, which can be as large as 100 degrees. In addition, the retro-reflection is insensitive to platform jitter. Despite this very generous pointing tolerance on the small platform, the retro-reflected beam has a divergence equal to the diffraction-limit of the retro-reflector (typically about 200 micro-radians). Thus the small platform maintains the low probability of intercept of a conventional optical communications link, but gains the loose pointing advantage of an omni-directional RF link.

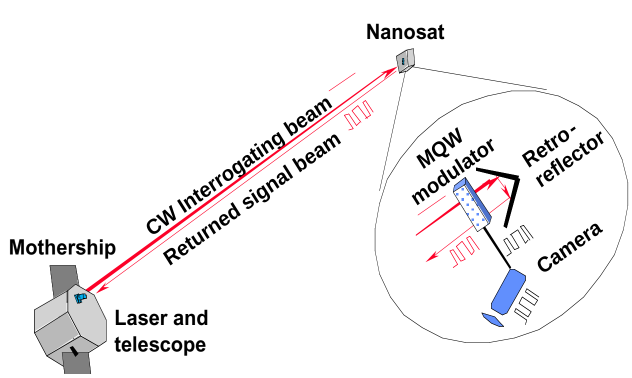

Figure 2 — Schematic diagram of a large platform communicating with a lightweight nano-satellite outfitted with a modulating retroreflector

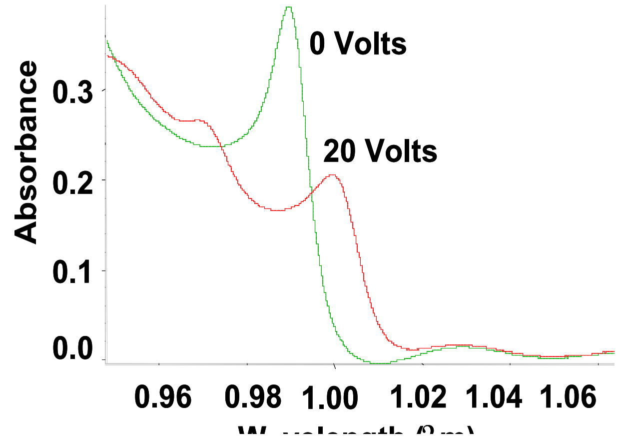

Figure 3 - Absorption spectra of large area MQW modulator for both 0 V and 20 V applied reverse bias

MRR systems utilizing ferroelectric liquid crystals have been demonstrated [1] but have generally been limited to kbps data rates. Over the past three years NRL has investigated the use of large area multiple quantum well (MQW) modulators to enable MRR systems. MQW modulators have many advantages including high data rates (>10˚Mbits/sec for the devices used in this work, potentially >1˚Gbit/sec for smaller devices), low voltage and power requirements, and good optical properties (very low wavefront distortion).

MQW modulators work by changing their absorption under the application of a voltage. Because they are absorptive modulators they have no angular or polarization dependence. The absorption spectra of an NRL large area (0.5 cm diameter) modulator are shown in Figure 3 and demonstrate the change in absorption near the band edge for different applied voltages.

These systems open up optical communications to platforms previously unable to use it, such as nano-satellites and unmanned airborne vehicles (UAV). Using these systems NRL has demonstrated free-space links to small UAVs in flight [2].

An important question about the use of such systems in space is the radiation tolerance of the MQW modulator. In most modulating retro-reflector systems the modulator will be exposed to radiation since it must have optical access to the outside of the spacecraft. A preliminary study conducted a year earlier using 20 MeV protons up to a total exposure level of 6.4 x$10^{10}$ protons $cm^{-2}$ failed to show any degradation in performance of the InGaAs/AlGaAs devices. To further investigate this question we examined the effects of proton irradiation on the most important characteristics of multiple quantum well modulators. Thus, the optical contrast ratio, the ability of the modulator to sustain a high applied electric field, and the response rate of the device were recorded for increasing radiation exposure levels. This is the first known study of the exposure of MQW modulators to high fluences of energetic protons.

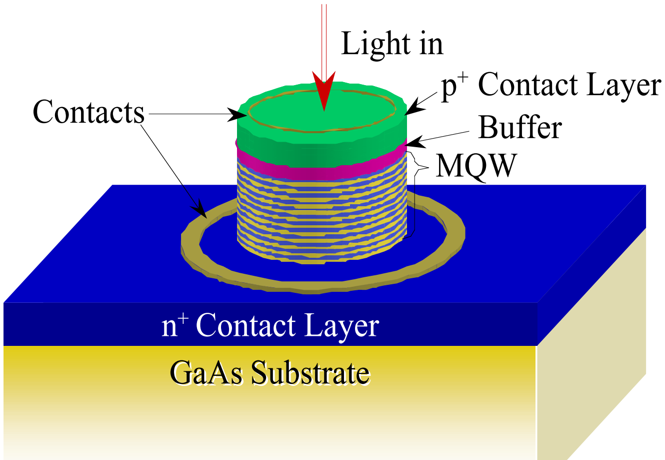


Figure 4 — Schematic of the MQW modulator geometry showing layer structure and electrical contacts for a surface normal optically transmissive device.

## 2. Multiple Quantum Well (MQW) Modulators

Three 0.5-cm diameter InGaAs/AlGaAs modulators were used in this series of tests. The modulators were designed for surface normal transmissive operation. The geometry of the MBE-grown samples is illustrated in Figure 4. All three were fabricated from the same wafer, with the layer structure shown in Table 1. Two of the modulators were segmented by etching through the top contact and MQW layers. Modulator 1 was unsegmented, modulator 2 was segmented into 4 pixels and modulator 3 was segmented into 9 pixels as shown in Figure 5. Segmentation allows for a reduction of sheet resistance resulting in an increase in speed, and a decrease in power consumption. Segmentation can also result in an increase in device yield by allowing isolation of any electrical defects.

*Radiation Exposures*

The modulators were mounted within a proton beam of diameter 3.5˚cm so that the radiation was incident on the top contact layer. A vacuum of $10^{-5}$˚Torr was maintained in the irradiation chamber. The MQW modulators were irradiated with a monoenergetic beam of 1˚MeV protons. The energy value was chosen such that the protons would pass through the MQW active region with negligible energy loss. The irradiations were performed incrementally with the devices being fully characterized after each irradiation step. The irradiation time, proton-beam current (as measured by a Faraday Cup), and cumulative fluence for each irradiation increment are shown in Table 2. The expected range for degradation was calculated from data for previous quantum well devices [3].

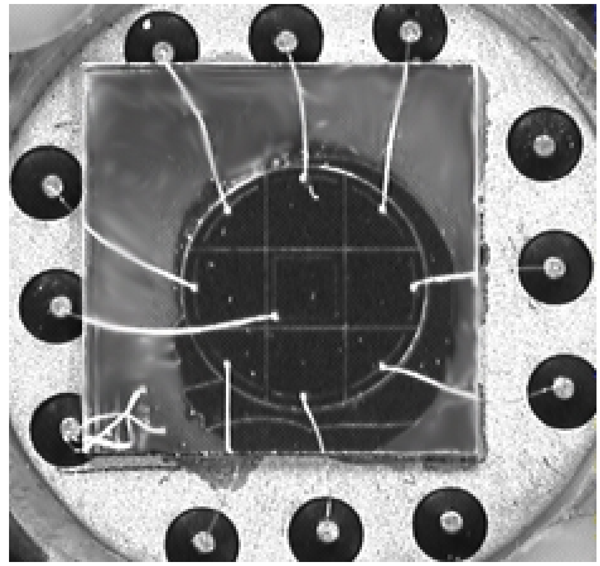

Figure 5 - Segmentation of MQW modulator #3 into 9 pixels. The individual wire bonds are evident

Table 2 — 1 MeV Proton Exposure

| Exposure number | Time (seconds) | Current (A/cm$^2$) | Cumulative Fluence (cm$^{-2}$) |
|---|---|---|---|
| 1 | 167 | $3.6 \times 10^{-8}$ | $8 \times 10^{11}$ |
| 2 | 630 | $3.6 \times 10^{-8}$ | $4 \times 10^{12}$ |
| 3 | 1230 | $2.1 \times 10^{-7}$ | $8 \times 10^{13}$ |
| 4 | 1307 | $3.6 \times 10^{-7}$ | $1 \times 10^{14}$ |
| 5 | 1307 | $1.8 \times 10^{-6}$ | $4 \times 10^{14}$ |

During irradiation, modulator 1 was set at a reverse bias of 15 V (normal operating bias). Modulators 2 and 3 remained unbiased during irradiation. In this way, modulator 1 was able to confirm our expectations that there would be no effect due to exposing the modulators with or without bias voltages.

Table 1 -- Layer structure of multiple quantum well modulator

| | | | |
|---|---|---|---|
| | Silicon Nitride | 1300 Angstroms | Anti-reflection coating |
| 1 _m | GaAs | p ($3x10^{18}$ cm$^{-3}$) | Top contact |
| 0.25 _m | GaAs | Undoped | |
| 75 period MQW | 80 $In_{.19}Ga_{.81}As$ well<br>100 $Al_{.35}Ga_{.65}As$ barrier | Undoped | |
| 500 | GaAs | Undoped | |
| 500 | GaAs | n ($3x10^{18}$ cm$^{-3}$) | Buffer |
| 400 _m | GaAs | n ($3x10^{18}$ cm$^{-3}$) | Substrate |
| | Silicon Nitride | 1300 Angstroms | Anti-reflection coating |

## 3. Performance Tests

Three electrical and electro-optical tests were performed prior to and after a series of stepped proton irradiations.

*Reverse Leakage Current*

To characterize the effect of irradiation on the reverse bias characteristics of the QW modulators, current vs. voltage (I-V) measurements were made in the dark from 0 to —20 V after each irradiation step. The irradiation caused a general increase in the dark reverse current. For analysis, the dark current values measured at -20V in modulator 3 are plotted in Fig. 7 as a function of fluence. The solid line in the figure represents a linear least squares (LSQ) fit of the data. The data shown are the sum of the current from 8 of the 9 pixel-segments. One pixel was found to be shunted prior to irradiation and hence was not included.

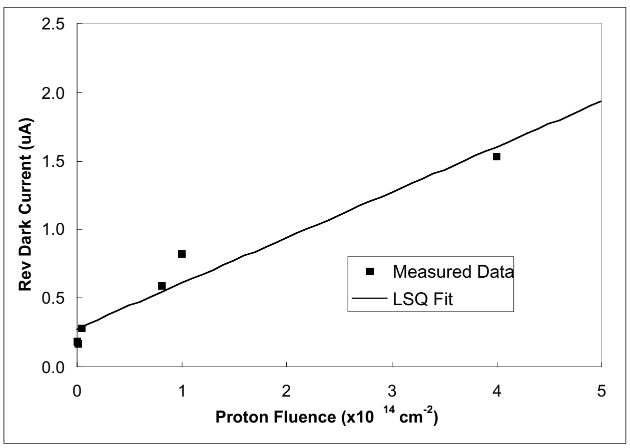


Figure 6 - Reverse leakage current measured at 20 V reverse bias after irradiation by increasing 1 MeV protons fluences. The solid line represents a LSQ fit of the data, and the data are seen to increase linearly with fluence.

The dark current is seen to increase linearly with increasing particle fluence at a rate of ~ 0.33 (μA-cm$^2$) determined from the slope of the LSQ fit line. The most likely mechanism for the dark current increase is radiation-induced point defects within the bulk GaAs material, which forms the p-i-n diode junction. These defects give rise to defect energy levels within the band-gap that act as trapping and recombination centers. The linear increase in dark current is a result of the fact that these defects are introduced linearly with increasing fluence. Deep level transient spectroscopy measurements are currently underway in attempt to characterize these defects.

*Modulation Response*

To assess the effect of irradiation on the temporal response of the QW modulators, the contrast ratio for the devices was measured after irradiation. The contrast ratio is defined as the ratio of the change in the modulated beam intensity to the quiescent value following a voltage pulse applied to the modulator:

$$CR = \_ / I \qquad (1)$$

with _ and *I* defined in Figure 7.

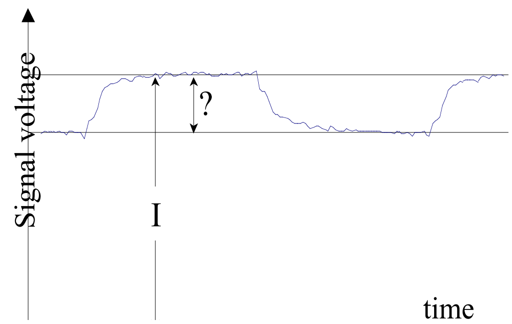


Figure 7 — Diagram illustrating_ and *I* used in contrast ratio definition

For the CR measurements, a 1 MHz square wave train was applied to the modulators, with high and low reverse bias values of 0˚V and 15˚V.

The CR was measured for the various pixels in modulators 2 and 3 as a function of particle fluence. The results are shown in Fig. 9. The data are somewhat scattered due to variability from pixel to pixel, but at the lower fluence levels the CR appears to be relatively stable with irradiation, to within 5%. At the highest fluence level, there does seem to be a distinct decrease in CR, indicating a degradation in device performance.

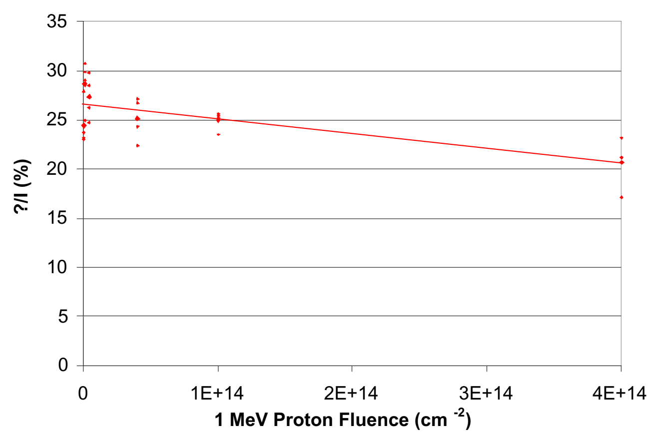


Figure 8 - Contrast ratio response to 1 MeV protons. Individual segment data for modulator 2 are shown as points. The solid line represents a LSQ fit of the average values.

At this point, it is important to put the levels of irradiation exposure into perspective in terms of radiation exposure levels typically encountered in the space environment. A low earth orbit is specifically chosen as that is a primary target application for these QW modulators. A 1,111 km, circular orbit, inclined 60 degrees with respect to the Equator will be assumed. Applying the formalism of

Summers et al. [4], the proton radiation environment experienced by a GaAs-based device after one year in this orbit is equivalent to a value of displacement damage dose ($D_d$) of about $1.5 \times 10^9$ (MeV/g). This assumes a 25 μm thick glass ($SiO_2$) window covering the modulator. The 1 MeV proton fluences experienced by the QW modulators in the present experiments (Table 2) can be converted to $D_d$ by multiplying by the appropriate value of nonionizing energy loss (NIEL), which is 0.5402 MeV $cm^2$/g in this case.

The results are shown in Table 3. As shown explicitly in the table, the irradiation levels studied here are equivalent to many years in Earth orbit, indicating that the present experiments significantly over-tested the devices. This was purposefully done to ensure that all of the damage modes in the devices were exercised. Thus, the QW modulators will be expected to operate with essentially no degradation for the duration of a standard space mission. Furthermore, these devices can be expected to operate satisfactorily in more harsh radiation environments such as medium Earth Orbits (MEO).

Table 3 - Comparison of irradiation levels of the present experiments with those experienced in Low Earth Orbit

| Fluence ($cm^{-2}$) | Equivalent $D_d$ (MeV/g) | Equivalent number of Years in LEO Orbit |
|---|---|---|
| $1 \times 10^{11}$ | $5.40 \times 10^{9}$ | 3.5 |
| $8 \times 10^{11}$ | $4.32 \times 10^{10}$ | 28.0 |
| $4 \times 10^{12}$ | $2.16 \times 10^{11}$ | 140.2 |
| $4 \times 10^{13}$ | $2.16 \times 10^{12}$ | 1402.4 |
| $1 \times 10^{14}$ | $5.40 \times 10^{12}$ | 3505.9 |
| $4 \times 10^{14}$ | $2.16 \times 10^{13}$ | 14023.6 |

*Absorption Spectrum*

The absorption spectrum of the devices was recorded using transmissive operation in a Fourier Transform Infrared (FTIR) spectrometer. The modulators were reverse biased at values of 0 V, 5 V, 10 V, 15 V, and 20 V and absorption spectra were recorded after each irradiation.

No degradation was observed until after irradiation up to the highest fluence of $10^{14}$ $cm^{-2}$, which has been shown to be an extremely high level of irradiation in comparison to the radiation environment in Earth orbit (Table 3).

In Figure 9, the absorption spectra of one of the modulators are shown, measured at 0 V before and after irradiation. Shown in Figure 10 is the difference in absorption spectra at 0 and 20 V applied reverse bias, measured before and after irradiation. The irradiation caused a slight decrease in the exciton absorption peak and a small shift of the peak to lower wavelengths. The exciton peak also appears to be somewhat broader after irradiation.

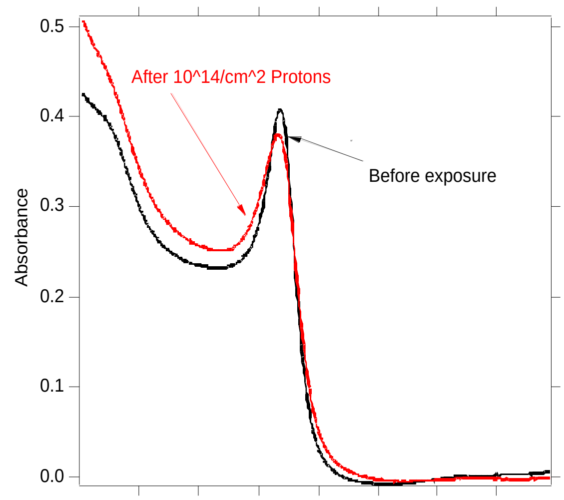


Figure 9 - Exciton peak shift in response to $10^{14}$ $cm^{-2}$ protons (measured at 0 V)

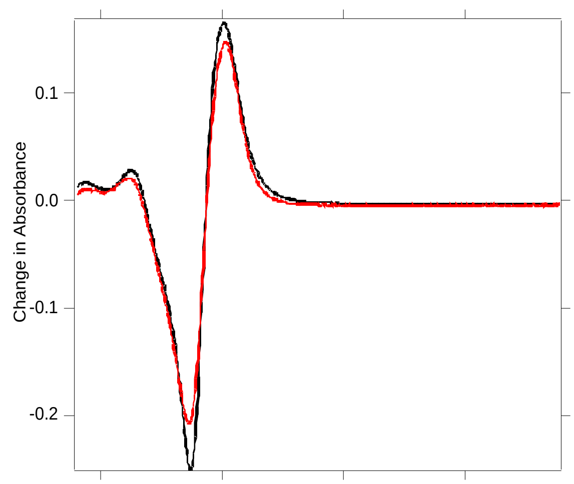


Figure 10 - Change in absorbance between 0 V and 20 V. Black curve is prior to radiation exposure, red curve shows degradation after an exposure to a 1 MeV proton fluence of $10^{14}$ $cm^{-2}$

## 4. Conclusions

The MQW modulators are quite insensitive to 1 MeV proton irradiation and should perform well in aerospace environments. This series of radiation exposures showed little change in modulator performance until a radiation exposure equivalent to hundreds of years in orbit. Of the tested characteristics, reverse leakage current was most affected, although not enough to affect device performance until well beyond a useful lifetime in orbit.

A preliminary analysis of the response of QW modulators to proton irradiation has been presented. At extremely high irradiation levels, some degradation of the device contrast ratio was observed. A shift in the exciton absorption peak was also observed after heavy irradiation.

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**William S. Rabinovich** was born in New York, NY, on November 28, 1961. He received the B.S. degree in physics from the State University of New York at Stony Brook in 1982 and the M.S. and Ph.D. degrees, also in physics, from Brown University, Providence, RI, in 1984 and 1987, respectively.

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His work at NRL has focused on the optical properties of quantum confined semiconductor materials. This work has included the development of multiple quantum well based spatial light modulators, nonlinear properties of intersubband transitions in quantum wells and large area multiple quantum well modulators for free space optical communications. He is the co-PI of the Quantum Well Modulating Retro-reflector program at NRL.

In 2000 Dr. Rabinovich became head of the Photonic Materials and Devices Section of the Optical Science Division at NRL.

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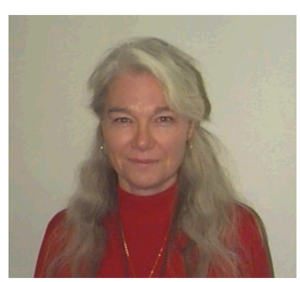
Dr. Messenger is a member of the IEEE Nuclear and Plasma Sciences Society.



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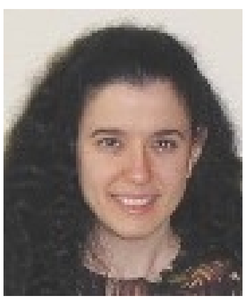

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In 1998, she joined the Naval Research Laboratory in Washington, DC. She has worked on HBTs on AlGaAs/GaAs, InAlAs/InGaAs and InP and Sb-based heterostructures, AlGaN/GaN HEMTs, optoelectronic devices, MQW modulators, resonant tunneling diodes, photovoltaic cells, and non-destructive electrical characterization techniques and Deep Level Transient Spectroscopy. She is a member of the IEEE, SPIE, AAUP, ASEE, the Electrochemical Society, Washington Academy of Science, New York Academy of Science, a member of the Technical Program Committee of IEEE-MTTs (1995-present), active member of the ad-com of IEEE-MTT Washington DC- Northern Virginia Chapter and listed in Who's Who. Her current research interests include the development and study of high-speed high-power electronic and opto-electronic devices in exploratory materials. Dr. Ikossi has single handedly developed the device fabrication process and processed the MQW optical modulators reported here.

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In 1989, he joined the Naval Research Laboratory, Washington, DC, as an Office of Naval Technology Postodoctoral Fellow. His research included GaAs *nipi* superlattice devices and optimization of interfaces in heterostructures grown by molecular beam epitaxy (MBE). Since 1991, he has been an Electronics Engineer in the High Frequency Devices and Materials Section of the Microwave Technology Branch at the NRL. His present research interests include the MBE growth of nitrogen- and arsenic-based III-V compounds, and the electronic and optoelectronic properties of novel III-V compound devices. His photograph is available in IEEE Trans. Electron Devices 44(2), 350 (1997).